Analysis of substances with Contactless Conductivity Detector (CCD) after Capillary Electrophoresis (CE)
1. Abstract

This study evaluated the possible uses for a custom-made Capillary Electrophoresis Contactless Conductivity Detector (CE-CCD). One of the key objectives was to determine whether measurements of conductivity with the device could replace UV-spectroscopy to analyze a range of samples, in particular PVA-MB and monosaccharides. Furthermore, to determine the feasibility of using the specific device as a substitute for UV-spectroscopy analysis, two commercial reference devices were used: one contact based conductivity detector and one potentiostat. Changes in resistance and voltage drops of samples containing the analytes were used to determine whether the analysis with the custom made CE-CCD could replace analysis with UV-spectroscopy.

The signal from the PVA-MB compared to variation in the signal of the background electrolyte was discovered to be too great for CE-CCD to be applied as a substitute for UV-spectroscopy. However both monosaccharides analyzed in the study, glucose and galactose could be detected. Glucose could accurately be detected down to 50 μM and galactose down to 25 μM. A semi-empirical calculation estimated a lower limit of 5 μM for glucose and roughly 8 μM for galactose.

PVA-MB could not be detected with the custom made CE-CCD while the monosaccharides can be detected in a range low enough to allow the detector to replace UV-spectroscopy for analysis. The best measurements taken with the detector were not as low as the best data found for UV-spectroscopy, but similar electrochemical applications were found to have reached similar or better values. Further development of the detector may lower its limit of detection to approach and possibly exceed the better measurements taken with UV-spectroscopy.
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2.1 List of Abbreviations
BGE – Background electrolyte
CCD – Contactless Conductivity Detector
CE – Capillary Electrophoresis
CTAB – Cetyl Trimethyl Ammonium Bromide
EDLC – Electrochemical Double-Layer Capacitor
LoD – Limit of Detection
PVA-MB – PolyVinyl Alcohol Micro Bubbles
UV-Vis – Ultra Violet-Visible Spectroscopy

2.2 Technical Terms
Electropherogram – Plot diagram, result of electrophoresis
EOF mobility – Electrophoretic mobility: the proportionality constant that relates drift velocity to electric field strength, specific for every solution.
Milli-Q water – Ultrapure deionized water
NAND gate – Negative-AND gate, generates square voltage wave
Impedance – The complex electrical resistance

3. Background and Objective
The objective of this project is to evaluate and develop the detection method of a contactless conductivity detector (CCD), paired with capillary electrophoresis (CE). Substances of interest in the analysis include polyvinyl alcohol micro bubbles (PVA-MB) and monosaccharides. Results will be confirmed with a direct contact conductivity detector and a potentiostat. It is also of interest to evaluate the importance of sodium benzoate in the separation of monosaccharides.

4. Theory

4.1 Capillary Electrophoresis (CE)
CE is an effective method for separation of charged substances. The process is driven by the different charges of the substances. When an external electric field is applied over the capillary, by means of two electrodes supplying high voltage, the substances will either be attracted or repelled. This causes a bulk flow inside the capillary, due to the electro osmotic flow, EOF. There the substances will move with different velocities depending on charge and size. Because of the difference in migration times, the substances will reach the detector separately [1]. An illustration of this can be seen in Figure 0.

![Figure 0](image)

Figure 0: A schematic CE-CCD showing a cross section of a capillary with solvated ions moving through it. Above and below the capillary are the CE- and CCD- electrode potential connections shown respectively. Also shown are the electro osmotic flow profile (left of the CCD-electrode connection) and the negatively charged capillary wall.)
4.1.1 Ionic Conductivity (in Solutions)

Ionic conductivity is the ability to transfer charge through the movement of ions, from one site to another. In CE, the ionic conductivity is based on the different velocities of the electrolytes in the electric field. The force that act on each ion, \( F = qE \), is a function of the applied electric field, \( E \) and the intrinsic charge of the ion, \( q \).

For the case of a particle traveling through a fluid, Stokes' law expresses the friction force on the particle that has to be overcome:

\[
F = -6\pi\eta rv \quad (1)
\]

Where \( \eta \) is the viscosity, \( r \) is the radius and \( v \) is the velocity. If the friction force is set equal to the expression of force in the form of electric field and charge one obtains

\[
qE = -6\pi\eta rv \quad (2)
\]

Continued conversion gives that the drift velocity is proportional to particle charge and electric field strength but inversely proportional to particle size.

\[
v = -\frac{qE}{6\pi\eta r} \quad (3)
\]

\( \frac{q}{6\pi\eta r} \) can be rewritten as \( \mu_e \), the electrophoretic mobility, which is the proportionally constant that relates velocity to electric field strength. \( \mu_e \) is specific for every solution. The relation is as follows:

\[
v = \mu_e E \quad [2] \quad (4)
\]

---

**Figure 1**: A schematic CE-CCD showing a cross section of a capillary with solvated ions moving through it. Above and below the capillary are the CE- and CCD- electrode potential connections shown respectively. Also shown are the electro osmotic flow profile (left of the CCD-electrode connection) and the negatively charged capillary wall.

Total mobility of substances (\( \mu \)) in the capillary equals the mobility of the ion (\( \mu_e \)) plus the EOF mobility (\( \mu_{EOF} \)), that is \( \mu = \mu_{EOF} + \mu_e \).

**Figure 2**: Illustration of the mobility of the substances
4.2 Contactless Conductivity Detection (CCD)
Capillary Zone Electrophoresis - Contactless Conductivity Detection, CE-CCD

Basic principle
The basic principle for the CCD is to use samples as part of a variable capacitor. In contrast to contact conductivity detection where the electrodes are in contact with the samples, the electrodes in contactless conductivity detection are connected to an intermediate medium transmitting the electrical field, in our case the capillary walls. By applying a voltage across two capillary walls, with two electrodes, an electrical conductance is obtained across the inner diameter of the capillary. Implicitly, the conductivity for the species passing the electrodes can be calculated from the resulting currents and voltages [1]. A simplified model is provided in Figure 3.

![Figure 3: Simplification of system. To the left is an illustration of the system with the capillary in the middle. To the right is an electrical schematic modulation where E₁ is the electrolyte that provides the resistance, with c₁ and c₂ as the capacitors. V is the voltage meter that provides the raw data. The symbol at the bottom is the voltage source.](image1)

Plotting the obtained voltages against time yields an electropherogram where a baseline represents the conductivity of the background. Increases and decreases of the voltage signal represent different species passing the detection site [1]. An example electropherogram can be seen in Figure 4.

![Figure 4: A schematic electropherogram.](image2)
Possible uses

- Quantitative analysis
  As the conductivity of the sample depends on the concentrations of the examined species, it is possible to quantify concentrations with the help of references and calibration.

- Qualitative analysis
  The time and order of which different species pass CE can easily be determined with CCD and with references it is possible to identify species in an unknown sample.

Available CE-CCD detector

The accessible CE-CCD detector was constructed for an examination project comparing UV-detection to CCD. The conductivity of a sample can be determined in more than one way. This device applies a square voltage wave over a capillary and measures the resulting currents. Below is a step-by-step description of how the specific detector generates an electropherogram.

1. The NAND gate generates an alternating square voltage wave (Figure 5) over electrodes placed on opposite sides of the capillary. This induces a current, which passes through the capillary.

   ![Figure 5: An alternating square voltage wave.](image)

2. The signal of the current is caught and amplified by a current to voltage converter, which sends out an alternating square voltage wave.

3. A half-wave precision rectifier removes the positive signals of the wave (Figure 6).

   ![Figure 6: A square voltage half-wave.](image)

4. The voltage half-wave is converted from an alternating voltage wave to a direct one (Figure 7).
5. Two low pass filters removes high frequency signals and compensates for the offset to stabilize the baseline in the final electropherogram. Due to noise the baseline would not be stable if the offset is not compensated for.

6. An analogue-to-digital converter registers incoming voltage signals implicitly with a corresponding frequency as a digital number. Essentially a voltage is translated to binary codes a computer can read.

7. The registered signals are used to calculate voltages, which are plotted against time, and an electropherogram is generated by software. [1]

4.2.1 Electrochemical Double-Layer Capacitors (EDLC)
The typical example used to describe the basic functioning principle of a capacitor is two conducting plates, separated by an isolator. When an electric potential is set up between the plates they will polarize the surfaces of the electrodes. The positive electrode gathers the negative charges, while the positive charge is gathered at the negative electrode.

What are usually referred to as super capacitors or ultra capacitors, are technically EDLC. The working principle of the EDLC sets it apart from conventional capacitors. The main difference is that the capacitance is in an electrochemical double-layer, sometimes referred to as a Helmholtz double-layer, instead of in between two macroscopic plates. This double-layer is formed as a charge distribution along the phase boundaries between electrode and electrolyte, by having positive ions pulled towards the negative electrode. Electrochemical double-layer capacitors have been made with power densities of up to $10^5$ W/l [3][4][5][6].

4.3 Direct Contact Conductivity Detectors
The electrical conductivity meter works by a potentiometric method reading of four different cylindrical electrodes placed along the edge of the tube. The conductivity meter is calibrated using electrolyte solutions of well-known conductivity.

4.4 Potentiostats
The working principle of a potentiostat is that it keeps the potential of the working electrode relative to the reference electrode at a constant level. This is done by the potentiostat by adjusting the current of the system through a high-impedance feedback loop, as instructed by a program supplied by a function generator. The job of the potentiostat can be seen as being to force the current through the working electrode, which is required to keep the potential constant across working and reference electrodes [7]. In the present study the potentiostat was used to run electrochemical impedance spectroscopy to measure the sample resistances.

5. Previous Research
CE-CCD is a relatively versatile detection method that can be used to analyze samples of different substances. Previous research has been performed in the field, analyzing samples of sugars, amino acids and copolymers, among other substances. At KTH, the relevant studies include two master theses; one about the construction and development of a CE-CCD, and one about analyzing polyvinyl alcohol bubbles with CE-UV.

- The study of sugars found CE-CCD to be a suitable analyzing method due to its low cost, simplicity and the high number of analytes that can be measured. The peaks for the analyzed sugars were clear and differentiated [8].
- When analyzing amino acids in human plasma, it was determined that the CE-CCD method could detect 22 out of 24 amino acids in the plasma. The method was considered to be a feasible option for analyzing amino acids [9].
- For detecting copolymers, CE-CCD was found to be more informative than other analyzing methods, due to the peak directions, which gave insight in whether the polymers were copolymers or homopolymers [10].
- At KTH, a CE-CCD was developed as a master thesis. A study of monosaccharides suggests that the CE-CCD gives clear results and liable linear correlations and that the limits of detection are 400 μM for glucose and 500 μM for galactose [1].
- Another KTH study examined the detection of polyvinyl alcohol bubbles by CE and an UV-detector. The study found it to be possible, but was unable to differentiate between whole and broken bubbles [11].
- A study from the University of Amsterdam of quantitative analysis methods for sugars investigated the performance of different methods to quantify sugars. The study found that levels down to 0.1 μM could be detected with UV-Vis spectroscopy [12].

6. Execution of Experiments

6.1 Materials
Both techniques included the following substances:

- Sodium hydroxide (NaOH), sodium benzoate and galactose were supplied by Sigma-Aldrich, Stockholm, Sweden.
- The Cetyl TrimethylAmmonium Bromide (CTAB) was from Hopkin & Williams LTD, London, England.
- The glucose was from AnalAr, Poole, England.
- Di-potassium phosphate (K2HPO4) was from KEO lab, Stockholm, Sweden.

All solutions were prepared with Milli-Q water (18.2 MΩ/cm) produced by a Millipore Synergy 185, Darmstadt, Germany.
The pH was measured using two-point calibration. The pH electrode was purchased from Hamilton and connected to a WTW pH 330 pH Meter. The pH calibration buffer solutions were also manufactured by the same company.
The CE-CCD was constructed as a master project by a chemical engineering student and has a 1m long capillary [1].
The conductivity meter display was a Consort K912.
The electrode was a SK41T
The potentiostat was a Gamry G 750

Stock solutions prepared:

- 50 mM water-dissolved Galactose for CE-CCD BGE
- 50 mM water-dissolved Glucose for CE-CCD BGE
- 0.5M water-dissolved Glucose for direct contact conductivity detector
- 0.5M water-dissolved Galactose for direct contact conductivity detector
- 5mM water-dissolved CTAB for CE-CCD BGE
- 3mM water-dissolved CTAB for direct contact conductivity detector BGE
• 1M NaOH solution for pH control of BGE
• 50mM water-dissolved K₂HPO₄
• 3.74•10⁸ PVA-MB/mL water solution
• 20 mM sodium benzoate

6.2 Methods

6.2.1 CE-CCD

Samples prepared:

- 200μM Galactose
- 100μM Galactose
- 50μM Galactose
- 25μM Galactose
- 200μM Glucose
- 100μM Glucose
- 50μM Glucose
- 25μM Glucose

The samples were produced by diluting liquid from the stock with Milli-Q water. The BGE was produced by diluting the CTAB-solution with Milli-Q water to 1.5mM and adding a small amount of NaOH to reach the desired pH (pH 11.6). The capillary was rinsed with 1M NaOH for 30 min at the start of each day experiments were conducted. The system was then rinsed with Milli-Q water for 15 min to clean out any remains of NaOH. A 15 min rinse with BGE was conducted after each water rinse, as well as for 10 min between every other sample run, as the BGE was pH-controlled and replaced after two measurements.

Each sample was run through the system three times in order to increase the accuracy of the measurement. The amount of noise also varied heavily between measurements and multiple measurements increased the possibility of getting at least one reading with a low level of noise.

The samples were induced electrically with a switch that was manually activated for five seconds. Both the injection and the run were set at 20kV.

6.2.2 Potentiostat and Direct Contact Conductivity Detector

For the Potentiostat and direct contact conductivity detector used to confirm results, both PVA-MB and monosaccharides (glucose and galactose) was analyzed. The PVA-MB was analyzed with the potentiostat and the monosaccharides were analyzed with the direct contact conductivity detector. This was due to the small volumes of PVA-MB, which were too small to be measured with the direct contact conductivity detector.

PVA-MB samples prepared:

- 1.87•10⁸ PVA-MB/mL (1:1)
- 3.37•10⁸ PVA-MB/mL (1:10)
- 1.78•10⁶ PVA-MB/mL (1:20)
- 1.21•10⁵ PVA-MB/mL (1:30)
- 9.16•10⁴ PVA-MB/mL (1:40)
- 7.29•10⁴ PVA-MB/mL (1:50)
- 6.17•10³ PVA-MB/mL (1:60)
- 5.24•10³ PVA-MB/mL (1:70)
- 4.58•10² PVA-MB/mL (1:80)
- 4.11•10² PVA-MB/mL (1:90)
- 3.74•10² PVA-MB/mL (1:100)

Numbers within parentheses represent relation (Stock:BGE).

The BGE consisted of 12.5mM K₂HPO₄, pH-adjusted to 11.97.
Filter papers were punched out to small circles, 8mm in diameter. For each sample, a filter paper was placed with an isolating holder in between the working- and the reference electrode of the potentiostat. The filter paper was then soaked in 25 μl sample solution. The main potentiostatic measurement consisted of a program measuring the impedance created by the sample solution and plotting Nyquist curves.

Monosaccharide samples prepared (both galactose and glucose):
- 5000 μM
- 4000 μM
- 3000 μM
- 2000 μM
- 1000 μM
- 500 μM
- 100 μM
- 0 μM

Tests were conducted with two different buffer solutions, one with 1.5 mM CTAB, and one with 1.5 mM CTAB and 10 mM sodium benzoate. The pH was adjusted to 12. Eight 10 mL test vials were filled with buffers with sodium benzoate and eight more were filled with buffer without sodium benzoate. The test vials were then filled with different sample volumes according to the set of concentrations wanted. An electrode (SK41T) was then used to measure the conductivity of the samples. The average value of three measurements was used in the plots.

6.3 Results and Discussion

6.3.1 Potentiostat and Direct Contact Conductivity Detector

![Impedance of various concentrations of PVA-MB](image)

*Figure 8: Variation of impedance of various concentrations of PVA-MB. As can be seen, no trend is found. The variation of impedance corresponding to sample concentrations is not consistent.*
Figure 9: Impedance variations conducted with CTAB without any PVA-MB. To further investigate the variation of impedance in the buffer solution, five consecutive tests on the same buffer was conducted. The samples ranged between 26.5Ω to 31Ω, a variation of 15%, and well above any impedance change that could be contributed by the addition of PVA-MB.

Due to the fact that the CE-CCD was in need of repair at the start of the project, the PVA-MB was first analyzed with the potentiostat. The working hypothesis was that PVA-MB would lower the conductivity of the sample, indicating that lowered concentrations of PVA in the sample would cause an increase in conductivity. As can be seen in Figure 8, no such trend could be detected. The different concentrations appeared scattered and without pattern. The strength of the analyte signals was also low, causing fluctuations in the BGE to alter the results significantly. Figure 9 shows impedance variations in the CTAB. The lack of correlation and the low signal strength caused a change of focus from PVA-MB to monosaccharides, which was known to be able to be detected in the CE-CCD. Further results from the PVA-MB analysis can be found in the appendix: Figure 14 and Figure 15 showing the Nyquist curves and an experiment with a different buffer, yielding similar results.
Figure 10: Conductivity of samples containing glucose or galactose in CTAB and sodium benzoate. The slope of the curve for galactose is steeper in a buffer solution containing sodium benzoate than in one with only CTAB.

Figure 11: Conductivity of samples containing glucose or galactose in CTAB. The slope of both glucose and galactose curves is less steep than in CTAB with sodium benzoate.

The study of the relation between stability of conductivity of monosaccharides and sodium benzoate indicate that sodium benzoate play a role in the stability. When comparing Figure 10 and Figure 11, it should be noted that the saccharides have steeper slopes with the sodium benzoate, especially in the case of galactose. A steeper slope indicates a higher response in the sample. Without sodium benzoate, the lines intersect at one point (Figure 11), indicating that the monosaccharides have the same...
conductivity at some points without sodium benzoate. It can also be noted that sodium benzoate causes a higher conductivity of the BGE.

6.3.2 CE-CCD
To calculate the semi-empirical lowest possible concentration, which can be detected with the CE-CCD detector at hand, it is necessary to make some assumptions:
- Voltage drops caused by samples are assumed to be proportional to the concentration of the sample.
- The baseline can be estimated as the first stable 15 sec period before any peak connected to the sample signal.

A standard deviation of the noise was calculated, and the result was then used to calculate the lowest limit of detection as three standard deviations subtracted from the normalized baseline. In the best measurement, only a single measure point deviated from the baseline before the monosaccharide signal (Figure 12, Table 1). The deviation was with a single unit of the digital quantity the analogue-to-digital converter used for measurements, in the middle of a series of 30 measuring points. The 30 measuring points starts at the green dot, and are counted backwards until the red dot.

For the main measurements, the samples were divided into glucose and galactose separately. An electropherogram for a sample containing both galactose and glucose can be found in the appendix, Figure 16.

Tables 1-4 summarize relevant data from the most important measurements.

Figure 12: Illustration of 50 μM Glucose signal in electropherogram.
Table 1: Measurements of 50 μM Glucose (pictured in figure 12).

<table>
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<th>Best Value</th>
<th>Average Value</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Average Value of Baseline</td>
<td>3.160336667</td>
<td>3.111717778</td>
<td>V</td>
</tr>
<tr>
<td>Standard Deviation of Baseline</td>
<td>0.000894614</td>
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<td>-</td>
</tr>
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<td>Value of Analyte</td>
<td>3.1311</td>
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<td>Voltage Drop of Analyte</td>
<td>0.029236667</td>
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<td>Limit of Detection, LoD</td>
<td>3.157652826</td>
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<td>Standard Deviations over LoD</td>
<td>29.68077926</td>
<td>19.43060748</td>
<td>-</td>
</tr>
<tr>
<td>Semi-empirical lowest detectable concentration (with current standard deviation)</td>
<td>4.5933849</td>
<td>7.93127788</td>
<td>μM</td>
</tr>
<tr>
<td></td>
<td>±3.341423588</td>
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</tr>
</tbody>
</table>

Electropherogram 50μM Galactose

Figure 13: Illustration of 50 μM Galactose signal in electropherogram.

Table 2: Measurement of 50 μM Galactose (pictured in figure 13).

<table>
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<td>Average Value of Baseline</td>
<td>3.106927</td>
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<td>Standard Deviation of Baseline</td>
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<td>Value of Analyte</td>
<td>3.0723</td>
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<td>Voltage Drop of Analyte</td>
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<td>Limit of Detection, LoD</td>
<td>3.101559</td>
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<td>Standard Deviations over LoD</td>
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<td>Semi-empirical lowest detectable concentration (with current standard deviation)</td>
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<td>μM</td>
</tr>
<tr>
<td></td>
<td>±1.074327517</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3: Measurement of 25 μM Glucose. The standard deviation over LoD indicate that this concentration can be detected.

<table>
<thead>
<tr>
<th></th>
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<th>Average Value</th>
<th>Units</th>
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<td>Average Value of Baseline</td>
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<td>V</td>
</tr>
<tr>
<td>Standard Deviation of Baseline</td>
<td>0.001819814</td>
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<td>Value of Analyte</td>
<td>2.9596</td>
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<td>Limit of Detection, LoD</td>
<td>2.963940557</td>
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<td>Standard Deviations over LoD</td>
<td>2.385164807</td>
<td>1.826706856</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4: Measurement of 25 μM Galactose. The standard deviation over LoD indicate that this concentration is just under what can be detected with the current standard deviation of baseline.

<table>
<thead>
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<td>Average Value of Baseline</td>
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<td>V</td>
</tr>
<tr>
<td>Standard Deviation of Baseline</td>
<td>0.001993507</td>
<td>-</td>
</tr>
<tr>
<td>Value of Analyte</td>
<td>2.9939</td>
<td>V</td>
</tr>
<tr>
<td>Voltage Drop of Analyte</td>
<td>0.00588</td>
<td>V</td>
</tr>
<tr>
<td>Limit of Detection, LoD</td>
<td>2.99379948</td>
<td>V</td>
</tr>
<tr>
<td>Standard Deviations over LoD</td>
<td>-0.05042376</td>
<td>-</td>
</tr>
</tbody>
</table>

Tests with both the CE-CCD and the direct contact conductivity detector shows an inverse correlation between sample concentrations and conductivity. This can be seen both in the direct conductivity measurements and on the voltage drop in the CE-CCD measurements.

With the CE-CCD, it was of interest to investigate if the previously found limits of detections could be lowered. This was done by testing different amplifier settings and removing sodium benzoate from the BGE, making the measurement more sensitive. However, it is of interest to notice the contradiction between this discovery and the one of the experiment with the direct contact conductivity detector. The improvement of results after the removal of sodium benzoate might be due to other factors, or that the detectors react differently. Measurements were conducted on concentrations ranging from 200 to 25 μM. For 100 and 200 μM, the results were unclear and the settings of the amplifiers were changed before analyzing lower concentrations, leading to a dismissal of the measurements of the two higher concentrations.

As can be seen in the results, it was found possible to detect concentrations as low as 25 μM for Glucose (Table 3) and 50 μM for Galactose (Table 2), with a semi-empirical LoD of just under 5 μM for glucose and around 8 μM for galactose. More noise appeared when analyzing 25 μM Galactose (Table 4), leaving negative standard deviations over LoD.

The stability of the baseline differed significantly between measures. At lower concentrations, the stability of the baseline is crucial. However, it is yet to discover why the stability differs. Due to the detector being a master project prototype it has a number of possible errors caused by growing pains. These error sources include contaminations in and BGE-coating of the capillary, electrical disturbances and pH of the BGE. With more measures and less noise, a more accurate result would likely be reached.
7. Conclusion

It is not possible to measure the concentration of PVA-MB with the detection equipment in this study. The direct contact conductivity detector shows an increase in response for samples in a BGE consisting of both CTAB and sodium benzoate.

In the study, it has been determined that it is possible to measure lower concentrations than the previous 400 μM for glucose and 500 μM for galactose. The new measured limits of the monosaccharides are 50 μM for galactose and 25 μM for glucose. A semi-empirical lower concentration limit was calculated to be just under 5 μM, with a stable baseline.

With the same detector, a LoD of 15 μM sodium and 45 μM lithium was determined in a previous study. Since a considerably lower LoD for monosaccharides was reached, these LoD could likely be lowered as well.

The LoD for the custom-made detector at 5 μM are comparable to the 0.1 μM, which can be obtained in more sensitive UV-spectroscopy measurements. Electrochemical measurements have been recorded to reach 0.05 μM [12].

For continued research, the most important goal is to increase the stability of the baseline in the CE-CCD to improve the accuracy of the measurements. This includes for example tests and optimizations of BGE.

8. Thank Yous

We would like to thank our supervisors Johan Jacksén and Simon Leijonmarck, as well as the helpful PhD students at the institute of analytical chemistry and the institute of applied electrochemistry.

9. References


10. Appendix

Figure 14: Trend lines of the Nyquist curves from the potentiostat measurement of PVA-MB

Figure 15: Variation of impedance in a NH₄HCO₃ buffer solution.
Figure 16: A measurement in the CE-CCD with 50 μM glucose and 50 μM galactose that shows the signals of the two sugars close to each other, see red arrow.